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Simulation Study of the Energy Performance of Different Space Heating Methods in Plus-energy Housing

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Abstract

Due to a shortage of energy resources, the focus on indoor environment and energy use in buildings is increasing which sets higher standards for the performance of HVAC systems in buildings. The variety of available heating systems for both residential buildings and office buildings is therefore increasing together with the performance of the systems.

This paper reports the results of a simulation study carried out using the commercially available building simulation software IDA ICE. The considered house was designed as a plus-energy house and it was located in Denmark. The dynamic building simulation model has been validated and calibrated with measurement data from the house in a previous study. The studied systems were radiant floor heating, warm-air heating through ventilation system and radiator heating. The energy performance of systems for achieving the same thermal comfort was compared.

The effects of several parameters on system energy performance for each space heating solution were investigated; floor covering resistance of the floor heating system, having a heat recovery on the exhaust in the ventilation system, and different working temperature levels for the radiator heating. For all cases the heat source was a natural gas fired condensing boiler, and for the floor heating cases also an air-to-water heat pump was used to compare two heat sources. The systems were also compared in terms of auxiliary energy use for pumps and fans.

The results show that the investigated floor heating systems had the best performance in terms of energy with a total energy saving of 23% compared to warm-air heating with heat recovery. It can furthermore be coupled to other heat sources than a boiler. The floor covering resistance of the floor heating system should be kept to a minimum to fully benefit from the low temperature heating potential since an increased floor covering requires higher average water temperatures in the floor loops and decreases the COP of the heat pump. The water-based heating systems required significantly less auxiliary energy input compared to the air-based heating system.

Furthermore, the results show that low temperature heating systems, as seen in floor heating in this study, can contribute to achieving plus-energy targets by minimizing the energy use for space heating purposes while achieving necessary thermal comfort for the occupants.

Keywords - Floor heating, warm-air heating, radiator heating, plus-energy house

1. Introduction

The amount of energy used for space heating accounts for a large part of the total energy demand of a building placed in colder climates. As the focus on energy use in buildings is increasing, different types of heating systems are also increasing together with the performance of the systems.

This study focuses on determining the energy use for different heating systems under the same thermal comfort conditions. A detailed definition of the investigated heating systems can be found in [1] in which the systems are investigated with the use of the exergy concept.

The simulation model used for the investigation was based on the competition house 'Fold' designed and constructed by the Technical University of Denmark for the Solar Decathlon Europe 2012 competition. The house has a floor area of 66 m² and a conditioned volume of 213 m³, and has two large glazing facades facing North (36.7 m²) and South (21.8 m²) respectively with a turn of 19° to the West.

Figure 1 shows the exterior views of the actual house.



Figure 1 – South façade (left) and North façade (right) of Fold

A detailed description of the house can be found in [2], [3].

2. Method

The investigation was carried out with the simulation software IDA ICE as the tool for assessing the thermal indoor environment and energy use. The initial IDA ICE model was constructed as a model with the properties as the actual house and has been validated with experimental measurements from the house [4]–[6].

A more detailed explanation of the general methods, internal gains, occupancy schedules etc. applied in this study can be found in [7].

For the investigations, the HVAC plant consists of a simple system mainly containing two 100 L water tanks for hot and cold water respectively. The cold water tank was only implemented due to limitations in the simulation software. The method of supplying the heat could quickly be altered without having to change any of the remaining properties of the HVAC system. A generic fuel heater was used in most of the investigated cases. The generic fuel heater heats the water in the hot water tank to the

desired temperature. For the floor heating cases, an air-to-water heat pump delivered the heating to the floor heating systems.

The investigation focused on three methods of supplying heat to the indoors: warm-air heating, heating with radiators and radiant floor heating. The main properties for the different cases are listed in Table 1, Table 2 and Table 3.

Table 1 – Case description for warm – air heating (WAH) [1]

Case	Heat recovery	Supply air temperature
WAH_NoHR	No	35°C
WAH_HR	Yes	35°C

Table 2 – Case description for radiator heating (R) [1]

Case	Supply temperature	Return temperature
R_45	45°C	35°C
R_55	55°C	45°C
R_70	70°C	55°C
R_90	90°C	70°C

Table 3 – Case description for radiant floor heating (FH) [1]

Case	Thermal resistance of floor covering	Supply temperature
FH_LoRes	0.05 m ² K/W	33°C
FH_MRes	0.09 m ² K/W	35.8°C
FH_HiRes	0.15 m ² K/W	39.8°C

For all cases the set-point for heating was set as 20°C and controlled by the operative temperature. The software normally controls the ventilation system by the air temperature. In order to get similar control systems, the ventilation system had to be controlled by the operative temperature. The solution was to implement a radiator with a negligible capacity of 1 W. The operative temperature reading from the radiator were connected to the ventilation system as a replacement for the air temperature input.

Radiators and radiant floor heating cases were set to be controlled by the operative temperature in the room with the use of a proportional controller.

The ventilation rate for the water-based systems was fixed at 0.5 h^{-1} with a supply temperature of 16.3°C with the use of heat recovery.

The properties of the radiators were calculated directly in the software from inputs of maximum power, supply temperature and return temperature. All radiators and floor heating systems were assumed to have a maximum capacity of 2500 W which was found as the required heating demand from the software. The radiant floor system was build up in the same manner as the one in the validated case with a temperature difference of 4°C between supply and return temperatures.

The radiant floor system was furthermore investigated in combination with an air-to-water heat pump instead of the generic fuel boiler. The properties of the heat pump were identical to the one used in the actual house with a COP of 3.47 and a total heating capacity of 8.73 kW [2], [4]. All simulations were performed with the weather file from the validated model, which contains weather data from the location of the house.

3. Results

The duration curves for the operative temperatures in the different cases are plotted in Figure 2. The temperatures are taken only for the investigated period from 1st of October to the 30th of April.

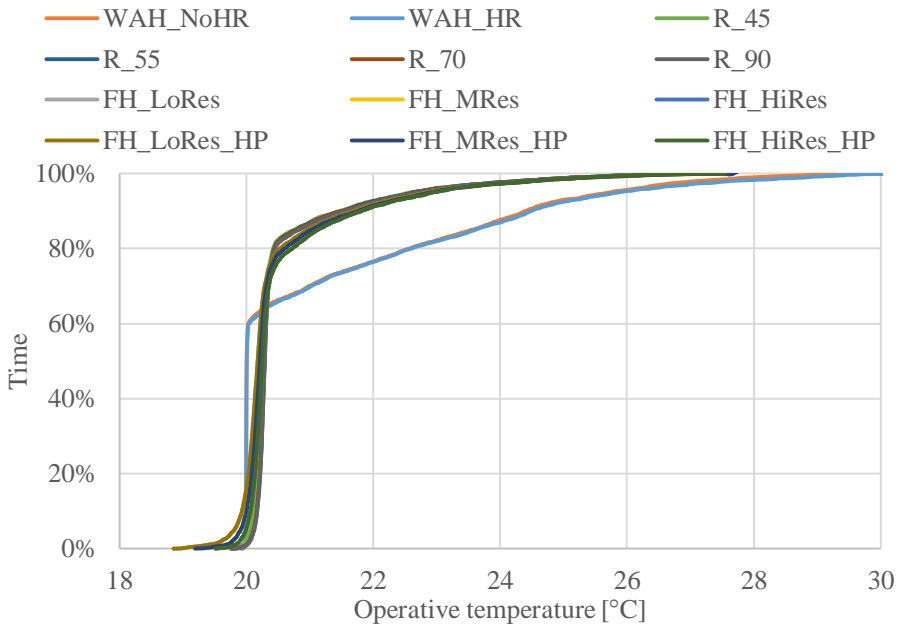


Figure 2 – Duration curves from simulations

The figure shows that the temperatures are clustered together for all water-based systems with a slight difference between water-based and air-based systems.

The plotted operative temperatures in Figure 2 show that the cases with warm-air heating had fewer hours below the set-point of 20°C compared to the water-based radiator and floor heating cases. The figure also indicates that the operative temperatures for the radiator and floor heating cases are more constant compared to the warm-air heating cases as the operative temperature is in the range of 20°C-21°C around 85% of the time. The time for the warm-air heating cases within these temperatures is around 70%.

In order to assess the thermal indoor environment, the temperature ranges stated in EN 15251 [8] was used. The ranges are given in Table 4 and the results are shown in Figure 3.

Table 4 - Temperature range for heating [8]

Category	Temperature range for heating (Clothing – 1.0 Clo)
I	21.0 – 25.0°C
II	20.0 – 25.0°C
III	18.0 – 25.0°C

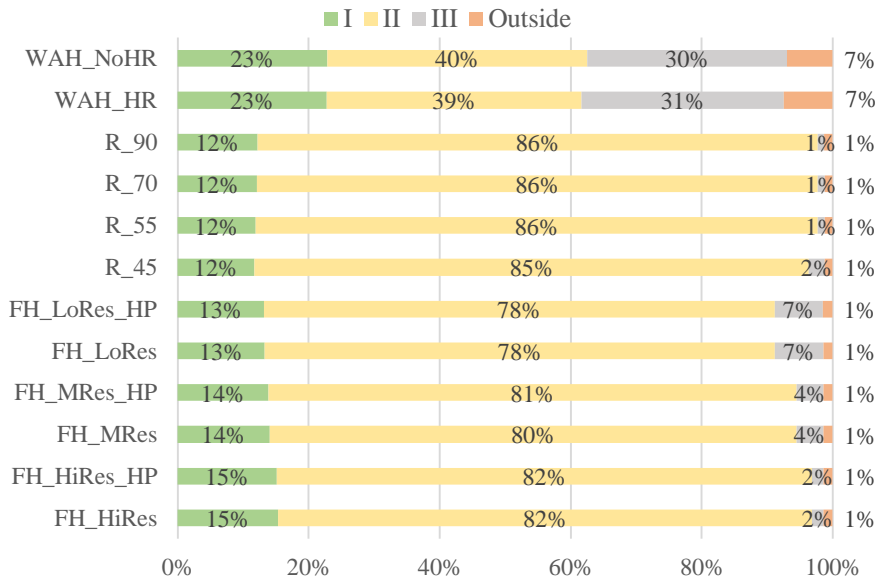


Figure 3 – Distribution of time in indoor environment categories

Figure 3 shows that the warm-air heating cases had the highest amount of time in indoor category I. The warm-air heating cases also had the largest fraction of time outside category I and II. The main reason for the increased time in category I is due to the ability of the warm-air heating to quickly adapt to the step changes whereas the water-based systems require longer time to change the thermal indoor environment, although the water-based system itself reacts immediately to the changes in the indoor environment. However, the increased time to affect the indoor environment for the water-based systems is also the reason for the small amount of time outside category I and II as the temperatures are kept more constant.

The primary energy use for heating and auxiliary energy for the different cases is shown in Table 5 together with the total primary energy use. A primary energy factor of 1 and 2.5 is used for Heating and HVAC aux respectively, except for the heat pump cases where an energy factor of 2.5 was used for heating as well [9].

Table 5 – Primary energy use (1st of October to the 30th of April)

	Heating [kWh]	HVAC aux [kWh]	Total [kWh]
WAH_NoHR	8693	944	9638
WAH_HR	4572	915	5487
FH_HiRes	4460	573	5033
R_90	4429	562	4991
R_55	4421	565	4985
R_70	4420	563	4983
FH_MRes	4397	577	4974
R_45	4392	566	4959
FH_LoRes	4348	581	4929
FH_HiRes_HP	3758	572	4330
FH_MRes_HP	3742	576	4318
FH_LoRes_HP	3697	580	4277

The table shows that in general the cases relying on warm-air heating used the most energy. They were followed by the radiator cases and finally the radiant floor heating cases. The floor heating system was found to be even more efficient when combined with a heat pump.

The differences between the radiator cases and the floor heating cases connected with a boiler are minimal. The point is underlined by the fact that the floor heating case with the highest thermal resistance performs worse in regards to the energy use compared to the radiator cases.

4. Discussion

The results with regard to the thermal indoor environment illustrated in Figure 2 and Figure 3 show that the temperatures inside the house were very close. The largest difference occurs between the air-based and radiant floor systems due to the difference in how quickly they can affect the thermal indoor environment.

It was a necessary condition that the thermal indoor environment was comparable in order to conduct a reasonable comparison of the energy use of the different heating systems.

The difference is clearly illustrated in Figure 2, where the amount of time below 20°C is higher for the water-based systems. The same figure also shows that the air-based systems have a larger amount of hours above 25°C resulting in approximately 7% outside any of the categories given in EN 15251 [8]. The performance of all systems may well be optimized by making individual control schemes.

The largest improvement was found between the two air cases with and without heat recovery. The improvement in energy use during the heating season was determined as 4150 kWh corresponding to an improvement of 43%. The main reason was found to be the amount of primary energy used for heating. Further analyses regarding the application of heat recovery can be found in [1].

The change of heating concept from warm-air heating to water-based radiators resulted in a reduction in the primary energy use. The main difference was found to be in the amount of primary auxiliary energy with a reduction of approximately 38% between warm-air heating with heat recovery and all water-based cases. The savings in energy use between warm-air heating and water-based radiator heating taken as an average of all four radiator cases was found to be 508 kWh corresponding to 9% less primary energy used.

The investigated radiator cases revealed that the working temperatures should be as low as possible in regards to the energy use. The difference was, however, found to be relatively small (32 kWh between R_45 and R_90) corresponding to a difference of less than 1%.

Replacing the radiator systems with a radiant floor heating system was found to be negligible in regards to the total amount of primary energy used. The compared values were taken as average values for respective cases; R_45, R_55, R_70 and R_90 for the radiators and FH_LoRes, FH_MRes and FH_HiRes for the floor heating. If the radiant floor system was combined with a heat pump instead of the generic boiler 671 kWh was saved resulting in an improvement of 13%.

For the radiant floor heating cases in general it was found to be important to minimize the resistance caused by the floor covering as this would lead to an increased amount of energy used [10]. The differences between the high resistance cases and low resistance cases were found to have an average value of around 2%. The difference was expected to be higher, but it could be a result of favorable operating conditions for the heat pump.

The total difference between warm-air heating and a radiant floor heating system with low floor covering resistance and combined with an air-to-water heat pump

(FH_LoRes_HP) was 1210 kWh during the heating season which is an improvement of 22%.

All results are found with the use of a dynamic simulation tool which is highly dependent on the input given to the software. The initial simulation model was validated with actual measurements, but changes such as the two 100 L water tanks, etc. could have had an effect on the results.

The obtained results were in some cases very close to each other and in those cases summation errors could have an influence in determining the optimal solution. This is due to the output files given by the software which is given as hourly average values with only two decimals.

5. Conclusion

The energy performance for different space heating systems (warm-air heating, radiator heating, and radiant floor heating) was investigated under similar thermal indoor conditions. The investigations were carried out with a dynamic building simulation model.

The investigation found that implementing heat recovery in the air handling unit is necessary as it was simulated to save up to 43% of the total primary energy used for space heating.

The energy performance could be improved by means of using water-based systems instead of air-based systems. The energy savings were calculated to 9% for radiators and floor heating systems heated by a generic boiler. The main difference was found in the primary auxiliary energy use which was approximately 38% less for all the water-based systems.

The study found that the radiant floor systems had the best energy performance when coupled to an air-to-water heat pump. The total energy savings from warm-air heating with heat recovery to a radiant floor heating system coupled to an air-to-water heat pump were 22%, while achieving similar thermal indoor environmental conditions.

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